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STATE OF THE ART
IN
PASSIVE SOLAR HEATING AND COOLING*

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ABSTRACT

Progress since the Albuquerque Passive Conference is discussed in terms of the major design approaches in buildings actually being constructed. Advantages and problem areas of each are described. Major areas where further work is needed are presented in detail.

The state of the art in passive solar energy utilization as of May 1976 was well described in the proceedings of the 1st Passive Solar Heating and Cooling Conference held in Albuquerque. As in every solar energy technology there have been tremendous advancements in the intervening 22 months. The purpose of this paper is to summarize the state of the art today.

Numerous solar buildings have been constructed during this time. More than anything else, learning from this practical experience has advanced the state of the art. More and more of these buildings are being instrumented and the data taken add greatly to the understanding of why the buildings perform as they do.

One area in which we have not made much progress is in agreeing to a simple and effective definition for what is meant by passive solar heating and cooling. The only reason that it is of any importance is that onlookers insist on a definition and each new entrant to the field invents his own. I have found the discussion tiring, confusing, and distracting. I would ask that we accept the following and get on with the job:

"A passive solar heating or cooling system is one in which the thermal energy flow is by natural means."

One framework in which to discuss the state of the art is to identify the major design approaches being used to passive solar heating and then summarize progress on each. These approaches can generally be separated into three categories:

Direct Gain: South wall or clerestory windows
Shading overhangs for summer
Internal mass

Indirect Gain: Thermal storage wall
Thermal storage roof
Solar greenhouse
Natural convective loop

Isolated Gain: Indirect gain situation in which there is a major separation (by either distance or insulation) between thermal storage and conditioned space.

The state of the art in each category is discussed below:

Direct Gain

This is the most popular design approach due to simplicity and perceived low cost. The main problem is providing sufficient thermal storage to decrease temperature swings to acceptable levels. The cost of the glazing is no more than that of the wall it replaces but thermal storage is expensive. Other problems are strong directional daylighting, glare, and ultraviolet degradation of fabrics.

In well designed direct gain buildings, January and February temperature swings are generally observed to be 15 to 20°F with peak swings of 20-22°F. I believe that these large swings and the other concerns mentioned are significant problems. Intrinsically, the building interior must vary in

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temperature if its surrounding surfaces are to store heat. The occupants of many of these buildings are so delighted to be warm in the winter, for a change, that they do not complain of occasionally being too warm. It is my own feeling that the bulk of the American public might not be so easy to please. It may be a mistake to try to promote both passive solar heating and a change of lifestyle at the same time.

We are now obtaining data on test rooms and on several direct-gain passive structures. The plot in Fig. 1 shows the temperature on the floor in a Santa Fe house which LASL is monitoring.

DIRECT GAIN BRICK FLOOR

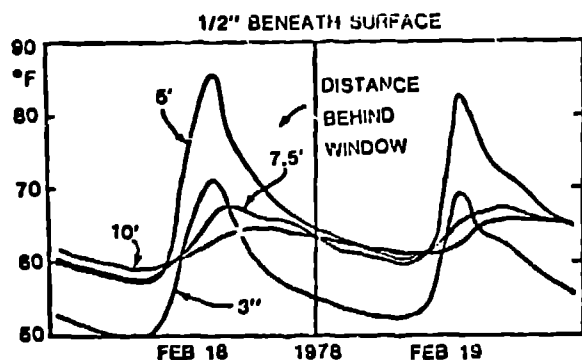


Fig. 1. Floor temperatures measured in a direct-gain house along a line extending north from the windows. The shadow line is about 5' 9". The measurement at 3" is low due to cold air falling down the window.

Although heat storage in the floor is economical, we know that it is relatively ineffective unless the floor is of masonry construction, is uninsulated on the surface, and is located in the direct (unshaded) sun. This is a severe requirement, seldom met. People like to put rugs, furniture, potted plants, and other things in their living space.

Thermal storage in side walls is also difficult because they are seldom located in the direct sun. Thus extensive and expensive mass must be deployed.

Thermal storage in the roof would be very effective because of the tendency of the heat to gravitate upwards toward it. This has not been used extensively however. The phase-change roof tiles being experimentally developed at M.I.T. may be an advance in this direction.

The state of the art in analyzing direct gain systems is poor. Although we can calculate the solar radiation transmitted through south glazing,

determining the distribution of that energy within the space by radiation and convection is especially difficult to analyze, but also especially important to understand.

Thermal Storage Walls

The state of the art is perhaps most advanced for thermal storage walls. This is because they are well known and relatively easy to handle. I feel that they are quite well characterized and we are able to predict their performance for different climates, wall material properties, glazing treatments, wall thicknesses, and degree of thermocirculation. We have a wealth of data on their performance and have validated our mathematical analysis techniques against these data.²

Like all indirect and/or isolated gain design approaches, the thermal storage wall circumvents two of the major difficulties with the direct-gain approach, both associated with admitting sun into the living space: the high lighting levels (glare), and damage to materials in the building by the ultraviolet. Placing windows in the thermal storage wall, as was first done by Doug Kelbaugh and later by others, is one effective means of mixing design approaches.

Another major advantage of the thermal storage wall is the reduction of temperature swings, by interposing a capacity effect between the solar gain and the living zone. This is especially true if the thermal storage wall is a solid material, such as concrete, which provides a smoothing of the temperature wave as it diffuses through the wall. Data taken from LASL test rooms operated without auxiliary heat indicated the following temperature swings on a series of sunny February days:

	Thermal Storage Mass, BTU/°F	Thermal Storage Surface Area/Glazing Area	Inside Daily Temp. Swing °F	Time of Inside Temp. Peak
Direct Gain Room	37	2.80	38	3:00 p.m.
16 in. Trombe Wall, (with vents)	32	0.84	26	4:00 p.m.
16 in. Solid Wall (no vents)	32	0.84	9	10:00 p.m.
Water wall	35	1.01	25	4:00 p.m.

These results are more extreme than would be observed in a passive building since the test rooms have a large ratio of collector area to load [$\sim 4.3 \text{ ft}^2/(\text{BTU/hr } ^\circ\text{F})$], and consequently the inside temperatures average about 50°F above the outside temperature on sunny mid-winter days.

Another advantage of a solid thermal storage wall is in providing a time delay between the absorption of solar energy on the outside of the wall and the delivery of that energy to the interior of the building. Characteristically, this time delay is in the order of 6 to 12 hours so that the maximum heating generally occurs in the evening at a time when it is most needed in a residential application. This time delay effect is quite evident in every thermal storage wall which LASL has monitored. Temperatures measured at different points within the wall are shown in Fig. 2 in data taken in Bruce Hunn's thermal storage wall.³ Two things should be noted on this plot: the increase in delay time to peak temperature, and the decrease in the peak temperature, as the wave progresses through the wall.

BRUCE HUNN TROMBE WALL

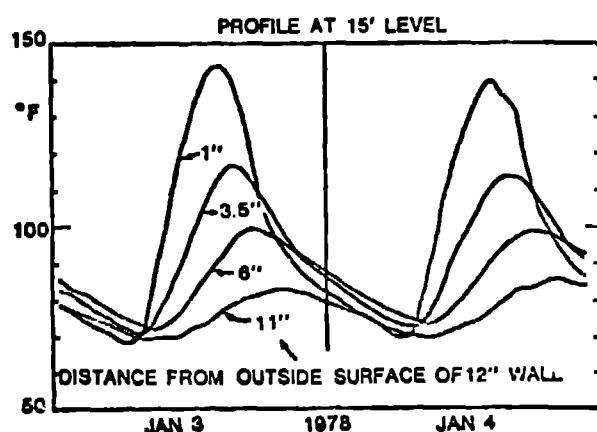


Fig. 2. Temperatures measured in a two-story thermal storage wall. The wall is made of 12" hollow concrete block with holes filled with mortar. The wall is double-glazed and has no vents.

The time delay effect allows for flexibility in thermal design. The building can be heated by direct gain or thermocirculation during the day and by the wall at night. The following table lists the characteristics of a solid concrete wall during sunny days with double glazing on the outside:

Thickness, Inches	Inside Surface Temperature Swing	Time Delay of Peak on the Inside
8	40°F	6.8 hrs
12	20°F	9.3 hrs
16	10°F	11.9 hrs
20	5°F	14.5 hrs
24	2°F	17.1 hrs

The thickness of solid wall which gives the maximum annual energy yield to the building is about 12 inches, independent of climate.⁴ However such a wall has rather large temperature swings and tends to be cold and uncomfortable during long cloudy periods. Thus the designer is led to consider thicker walls which provide more storage and a more stable inside surface temperature.

However, the major problem with Trombe walls is high cost of construction plus the related fact that they use up valuable space within the building.

Various different approaches to thermal storage walls have been implemented in an attempt to overcome these difficulties. Water in containers of various shapes and sizes has been used effectively. One interesting design by Wayne Nichols is a "water-loaded Trombe wall" consisting of cast concrete tanks of 4 ft x 8 ft x 10 in. outside dimension. The tank wall is 2 inches thick leaving a 6 inch cavity. After installation, a plastic bag is put in the cavity, filled with water and sealed. Data taken by LASL on this wall are shown in Fig. 3.

FIRST VILLAGE, UNIT 4

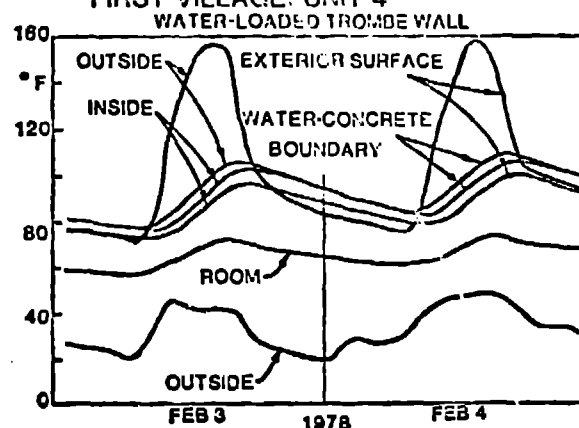


Fig. 3. Reflector-augmented "water loaded" Trombe wall." Temperatures are measured at the outside surface, at the boundaries between the water bags and the 2" concrete walls, and at the inside surface.

The wall is covered outside at night by a Steve Baer-style hinged insulating-reflecting door. Nichols concluded that future walls of this type should be made much thicker to provide longer heat storage and maintain the wall warmer and thus more comfortable during long cloudy periods.

Solar Greenhouses

A solar greenhouse is a mixture of the direct gain and thermal storage wall approaches. A more general description would be to call it a "sunspace"

instead of a greenhouse. The room on the south is a direct gain space with extensive glazing. It is separated from a living space on the north by a thermal storage wall. The building acts basically like a Trombe wall building with the advantages of the thermal storage wall, however the room on the south is a usable space quite suitable for the growing of plants.

I have become an advocate of this design approach because of its several advantages and because of my experience in living in such a home: Unit 1, First Village in Santa Fe, designed and built by Wayne and Susan Nichols. The design finesse incorporated into this house has produced an extremely stable thermal environment in the living areas. Typical temperature swings are 4°F in the summer and 5°F in the winter.

The principal means by which temperature swings are reduced is to utilize the principle of thermal buffering. Referring to Fig. 4, one zone (the outer space in the Trombe wall or the greenhouse in a greenhouse-house combination) is the solar collection zone and swings greatly in temperature; a second zone (the living space) is buffered from these fluctuations by a mass wall and is quite stable in temperature.

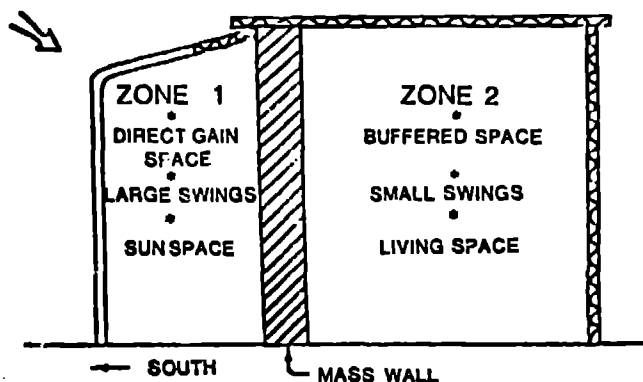


Fig. 4. Buffering of temperature swings in the living space by means of a two-zone structure. Hot air from Zone 1 can also be blown through a rock bed under the floor of Zone 2.

With a little care in thermal design one can arrange to have Zone 2 be quite stable in temperature.

One additional active technique used in my home has proven to be quite effective. Solar-heated air is blown from the greenhouse through a rock bed under the floor of the living space. A concrete slab on top of the rock bed increases its thermal mass and provides a delay in time of heat arrival by

conduction up through the floor slab. The warm floor is quite comfortable and offsets the tendency of the room to stratify in temperature.

Data taken on my home are very revealing. Auxiliary heating requirements are quite small. The backup is baseboard electric and is metered separately from our other electricity. Over a one year period of approximately 6400 degree-days, the total used was 857 kwhr (about \$33). The thermostat is set at 65°F and we have noted that almost all of the backup is required between 12:00 midnight and 6:00 a.m. (during the off-peak hours).

The mass wall separating the home from the greenhouse behaves like a Trombe wall but with less pronounced response since the surface area is much larger than the glass area. Data are shown in Fig. 5 for the upper east wall which is 10 inch adobe. This shows the primary heating.

The house is quite comfortable at 65°F since the walls and floors are also at that temperature or warmer.

FIRST VILLAGE, UNIT 1, SOLAR GREENHOUSE

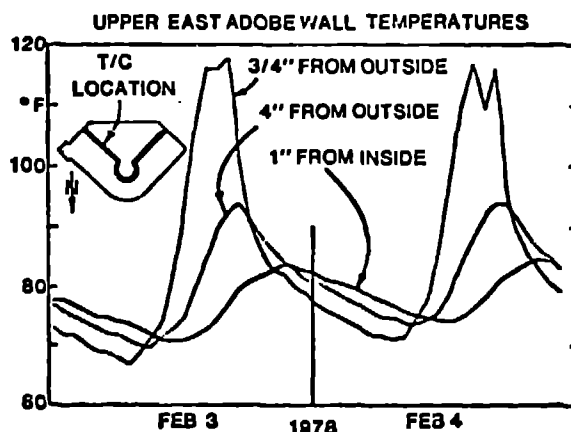


Fig. 5. Temperatures measured in southwest facing wall at second story level (see sketch insert). Dips in outside peaks are due to shadowing from greenhouse beams. Note that this wall is heated in the afternoon.

Attached solar greenhouses have become an extremely popular and effective means of retrofitting existing buildings for passive solar heating. Bill Yanda has popularized the do-it-yourself approach to solar greenhouse and continues his crusade to educate the country via his barn-raising style of greenhouse workshops.

One such greenhouse was instrumented by LASL and the results indicated a large net positive gain from the greenhouse to the living space.

The Solar Room Co., a small business which is manufacturing and selling double polyethylene inflated greenhouse kits, is conducting a series of experiments for the DOE. These consist of a

series of side-by-side test rooms, one without a solar greenhouse and three with a solar greenhouse. The rooms are thermostatically controlled and the energy required to heat them is monitored. Current data indicate a 30 to 40% reduction in the heating requirements of the rooms with the greenhouse. Thermal storage located in the floor of the north room was shown to be ineffective unless heated by greenhouse air forced by a fan.

Thermal Storage Roof

The thermal storage roof approach to passive solar heating and cooling has been popularized by the "Skytherm" houses of Harold Hay.⁵ We know that these work quite well in arid hot climates and we are now beginning to see more of these houses built.

The New Mexico State University, near the southern edge of New Mexico, has analyzed a "Skytherm" house with a thin concrete roof deck beneath the water ponds and predict that this should work well. They are well along in the construction of a house incorporating this feature which will be tested side-by-side with the existing active solar heated home next door.

In addition to the "Skytherm" approach, there is now an alternative design which is being marketed in the Phoenix, Arizona area. The basic idea is similar, but instead of moving insulation across the roof, the system uses a small pump to force water from a lower zone into an upper zone. The insulation floats between the zones. When the pump is on, the water is above the insulation and interacts with the environment. When the pump is off, the water seeks the lower level and the insulation rises up against the plastic cover. A house built according to these principles has been evaluated at the Arizona State University and found to work well.

Convective Loop

The thermosiphon water heater is in this category and a number of these have now been built within the U.S. It is one of the most inexpensive and reliable water heaters I know. A non-freezing version is now being marketed in which the water tank is double-jacketed and located above the collector. A non-freezing glycol solution carries the heat from the collector through the pipes to an annular space between the two tank walls. These systems work well without the need of either pumps or controls.

An air convective loop was built into the well-known house of Paul Davis. Another large air convective loop system has been built on a house in Santa Fe. The collection and storage is a passive design similar to that employed in the Davis house. However the distribution of heat to the house is through a conventional forced-air heating system utilizing underfloor ducts. The rock bed is in the return air path of this

heating system. Thus the system is a hybrid with passive collection and storage and active distribution.

Small convective air heaters are an effective retrofit for many applications. A simple window box air heater is quite effective if properly designed so that it will not lose heat at night. Many variety of different designs are coming forward and we can expect them to play an important role in passive energy utilization, especially in the retrofit of existing buildings.

DIRECTIONS FOR FUTURE WORK

The key issues in moving passive solar design into widescale use are:

- development of a simple quantitative basis for design;
- close integration of thermal, along with architectural, cost and functional considerations, into the building design process; and
- communication with the user community.

Major areas where further work is needed are:

I. MATHEMATICAL SIMULATION AND SYSTEMS ANALYSIS

A. Component Modeling

1. Simulation Analysis. A thermal network analysis approach has been developed and shown to be useful and appropriate. Performance is predicted using a full season of hour-by-hour weather and solar data taken at the locality of interest. The method is cumbersome but effective. Input routines need to be streamlined using computer graphics in an interactive mode.
2. Solar Gain Analysis. Calculations of solar transmission through glazing is well understood including considerations of shadowing and reflections. Data are needed in two areas: solar radiation measurements on vertical surfaces and its relationship to horizontal solar radiation, and the properties of glazings, especially with regard to the batch-to-batch variation, infrared transmission, and aging characteristics of plastics.
3. Radiative Cooling. Although theoretical models are available which correlate radiative heat flux with relative humidity, cloud cover, etc., more data are required to better understand how regional variations will affect radiation as a cooling mechanism.

4. Building Energy Loss Calculation. Although this is not strictly in the passive solar bailiwick, it is impossible to ignore the building heat requirements in designing for solar heat supply. Calculation of building envelope energy transfer is in fairly good shape but determining building air infiltration is largely an unknown and as better insulated buildings are designed this becomes a very significant part of load. There are simply no good models. The conservation effort should be intensified to thoroughly investigate this area.

5. Heat Flow Within a Building. Radiative energy transfer is well understood, however the convective effects are not. Experiments should be set up, models generated, and validated, especially as pertain to north-south and upper-floor/lower-floor convective air exchange within buildings.

B. Site Climate Analysis.

Although there is a mystique among architects about the importance of site and microclimate on building loads, there is almost no quantitative information available nor do any good models exist. These should be generated and validated especially as to the effect of wind and wind breaks, topography, ground effects, and vegetation.

C. Validation Procedures.

Validation presently consists of comparing observed temperatures with those predicted by simulation model calculations. A comprehensive validation methodology should be developed and used. Comprehensive data taken on a few buildings representing variation in building type and climate should be taken and disseminated as a data base for model validation.

D. Systems Analysis.

This consists of sensitivity studies, climatic studies, performance characterizations and comparisons, and economic trade-off studies for whole passive buildings. The tool is hour-by-hour simulation models. A major effort should be made to extend the current efforts in the following areas: identifying a methodology for choosing design weather periods, streamlining procedures, development and validation (vis-à-vis complex models) of simplified analysis models, and the analysis of available semi-quantitative and qualitative data to identify trends.

E. User-Oriented Design Techniques.

A major effort should be made to develop and disseminate design tools specifically tailored to three different classes of user: the designer-builder, the practicing architect, and the mechanical engineering firm. Simple "rule-of-thumb" design techniques for use in conjunction with present building energy analysis methods should be developed suitable for estimating passive solar buildings and published in user-oriented design manuals. More exact techniques should be developed suitable for use on desk-top programmable calculators and the emerging low-cost, stand-alone microprocessors, and these disseminated, again through appropriate manuals. Finally, computer-aided analysis techniques should be developed and packaged for analyzing larger structures where multi-zone and complex geometry, and self-shading considerations are especially important and cannot be handled by simpler methods.

F. Hybrid Systems.

Combinations of active and passive solar energy designs, called hybrid, are very attractive, especially the use of some fan-forced air movement. The preceding work should be structured to incorporate the ability to analyze hybrid designs and a thorough configurational analysis should be made to identify the most attractive hybrid approaches.

II. PERFORMANCE FACTORS, INSTRUMENTATION AND DATA ACQUISITION

A. Human Comfort.

The area of thermal comfort has been well researched and elaborate models based on extensive laboratory controlled testing of volunteer subjects have been devised. Current thermal comfort standards, however, are not flexible or broad enough to effectively deal with emerging issues--not just for passive buildings but for all buildings--such as adaptation and modified expectations, age, individual preferences and differences, and occupant control, participation and activity level. Passive solar brings up additional issues such as asymmetric radiation, cross ventilation, and perhaps even climate monotony. A reassessment of thermal comfort should be undertaken to obtain effective measures which account for these aspects perhaps even establishing the dollar value of thermal comfort. Measurements should emphasize realistic in-situ observations as well as responses of laboratory subjects.

B. Instrumentation and Data Acquisition.

The cost and time required to obtain reliable and comprehensive data needed to thoroughly evaluate solar buildings has consistently been underestimated. This experience should be factored into the monitoring of passive solar buildings noting that techniques devised for monitoring active solar systems are not directly applicable. Two instrumentation schemes should be identified--one directed to an in-depth evaluation and another directed to the obtaining of "critical" data required to assess net system effectiveness (determining how the building worked but not necessarily determining why it performed as it did). The second system should be quite inexpensive (less than \$2000) and would be intended for multiple applications to obtain "bottom line" data on many passive building design approaches in many climates. It probably should use a microprocessor to process the input and thus minimize the required output. Installation of the in-depth system should be made on only a few key buildings as required to obtain comprehensive data, setting realistic goals and allocating sufficient funds and manpower to obtain good results.

C. Reporting of Data.

Since there are no established procedures, the reporting of data is at the discretion of the reporter and is frequently haphazard. The key uses and users of data should be identified and a consistent format adopted.

D. Performance Measures, Testing Approach and Data Interpretation.

Presently there is no consistent way of evaluating the performance of passive solar buildings; this also is left to the discretion of the experimenter. Procedures should be established and adopted suitable for two classes of evaluations: a large number of passive buildings where only "critical" data are available, and selected few buildings which are extensively instrumented. Key measures which need further work are: methods of measuring air infiltration, the use of infrared thermography to take data, and devising simple, inexpensive, and reliable methods of obtaining necessary data, including mean radiant temperature and heat flux. Interpretation of data is difficult since the passive solar system elements are usually closely integrated into the building. Standard methods should be devised and adopted which are suitable for both wide-scale and in-depth use.

III. MATERIALS, COMPONENTS AND CONTROLS

A. Physical Properties and Material Development.

By and large, appropriate and adequate materials are available for passive solar applications. A major impediment is the lack of availability of usable information for the designer-builder, and there is widespread concern about the validity and applicability of manufacturers' published data. Standard test procedures and measures should be adopted and their use required. Handbooks should be updated periodically with new data. Key materials which should be emphasized in the testing are glazings, especially their optical, thermal, and aging properties, thermal storage materials, surface treatments of glazings and absorbers, and insulation materials. An ongoing search for new or improved materials should be conducted emphasizing these same areas and directed to improving their performance in passive solar applications.

B. Glazing and Movable Insulation Assemblies and Other Components.

Improved glazing assemblies are needed, designed for passive solar applications. The effect of joints, details and connections is not well known. Standardized testing and reporting procedures should be developed, adopted, and the results disseminated. Methods of maximizing solar gains and minimizing thermal losses, possibly through use of movable insulation, or conversely minimizing gains and maximizing heat exchange should be devised. Many other product opportunities exist in passive solar. These include thermal storage assemblies, heat pipes and thermal diodes, convective loop heaters, and reflectors. Methods must be found to provide for assurances of product performance and lifetime integrity.

C. Controllers, Actuators, and Sensors.

Conventional controls can meet most of the needs of passive systems but a few areas require special attention including solar gain control, ventilation control, and anticipating off-peak electric heating controls.

IV. IMPLEMENTATION

More than most technology developments, passive solar faces difficult barriers, which should be regarded as constraints and hurdles providing us with opportunities to develop effective solutions. Prompt implementation of passive solar on a national scale must be based on a careful analysis of these barriers incorporating the lessons learned from previous experience. Areas of concern are communications, governmental (at all levels), legal, social, and technical.

Incentive programs instituted by the government should be carefully designed to maximize passive solar participation. This is made difficult by the close integration of passive solar features into the architecture of the building in which both the solar collection and heat storage elements often serve dual roles.

Many opportunities exist for retrofitting passive solar in existing buildings and means of maximizing their implementation should also be sought.

A critical key to implementation is a proper recognition of product opportunities which exist for passive solar. The business community, already well geared up for active systems, will expand to develop and promote these new products and we will see a broadening of the present solar business base to incorporate both hybrid and fully passive systems.

ACKNOWLEDGEMENT

Much of the information presented in this paper was developed during the passive solar program planning process being conducted by the DOE. I am indebted to the many persons who contributed to this evaluation for their comments and contributions.

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